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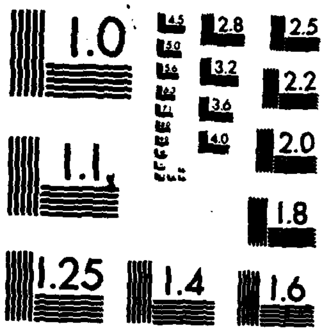

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EVALUATION OF THE SHORT ROD METHOD FOR MEASURING THE FRACTURE TOUGHNESS OF BERYLLIUM

MAY, 1979

TERRA TEK, INC.
SALT LAKE CITY, UTAH

FINAL REPORT - CONTRACT NUMBER DAAG46-78-C-0033

Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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The fracture toughness of CIP/HIP-1 beryllium was measured by testing five compact toughness (CT) specimens, following the ASTM E 399 method except for using K_F in fatigue pre-cracking of about 0.8 K_{Ic}^{Q} as opposed to the 0.6 K_{Ic}^{Q} required by E 399 (beryllium is very difficult to fatigue pre-crack). The CT measurements agreed very well with previous measurements of the toughness of beryllium. The tested CT specimen halves were then machined into short rod specimens, and the fracture toughness was measured by the

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short rod method. The average of the short rod measurements differed from the average CT measurement by about 2 percent. In addition, the short rod tests provided a measure of K_{Ia}, the stress intensity factor which allows a fast-moving crack to arrest. These results, together with the simplicity of the short rod test in which no fatigue pre-cracking is required, make the short rod method attractive for measuring the fracture toughness of beryllium.

FOREWORD

This study has been conducted by Terra Tek, Inc., Salt Lake City, Utah, under contract No. DAAG 46-78-C-0033 from the Army Materials and Mechanics Research Center, Watertown, MA. Mr. J. F. Dignam of the AMMRC was project manager, and Dr. S. C. Chou of the AMMRC served as technical monitor. The advice and guidance of Mr. Dignam and Dr. Chou in this study are much appreciated.

ABSTRACT

The fracture toughness of CIP/HIP-1 beryllium was measured by testing five compact toughness (CT) specimens, following the ASTM E 399 method except for using K_F in fatigue pre-cracking of about 0.8 K_{Ic} as opposed to the 0.6 K_{Ic} required by E 399 (beryllium is very difficult to fatigue pre-crack). The CT measurements agreed very well with previous measurements of the toughness of beryllium. The tested CT specimen halves were then machined into short rod specimens, and the fracture toughness was measured by the short rod method. The average of the short rod measurements differed from the average CT measurement by about 2 percent. In addition, the short rod tests provided a measure of K_{Ia}, the stress intensity factor which allows a fast-moving crack to arrest. These results, together with the simplicity of the short rod test in which no fatigue pre-cracking is required, make the short rod method attractive for measuring the fracture toughness of beryllium.

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INTRODUCTION

Beryllium is an important aerospace material because of its light weight, high modulus, and high heat capacity, coupled with good strength. It is a brittle material, however, and hence its fracture toughness is of concern. Although beryllium fracture toughness measurements have been made by a number of investigators[1,2], there is considerable scatter among the results obtained. The main difficulty in the fracture toughness testing has been obtaining a real crack in the test specimen, and this has led in some cases to the use of machined notches rather than real cracks. Attempts at fatigue pre-cracking according to ASTM E 399-74[3] have been largely unsuccessful or have proved quite expensive because of the extremely slow fatigue crack growth rate at crack tip loadings of no more than 0.6 K_{IC}. A subcommittee of the ASTM is currently attempting to standardize a new test procedure which would be especially adapted to, and limited to, beryllium.[4]

The recently developed short rod method of measuring fracture toughness[5,6] has been successfully applied to a number of very brittle materials, including fused quartz, ceramics and cemented carbides. One of the main advantages of the short rod specimen (Figure 1) is that the necessary pre-crack is created automatically during the test without any fatigue cycling, even in the most brittle materials. It therefore appeared that the short rod method might be ideal for rapid, economical tests of the plane-strain fracture toughness of beryllium.

This paper reports the results of a test series on beryllium whose objective was to compare critical stress intensity factors measured by the short rod method with those obtained by essentially the method of E 399-74.[3] The test series provided not only the desired toughness measurement comparison, which was very good, but also gave a measure of the stress intensity factor at the time of crack arrest of a rapidly moving crack in beryllium.

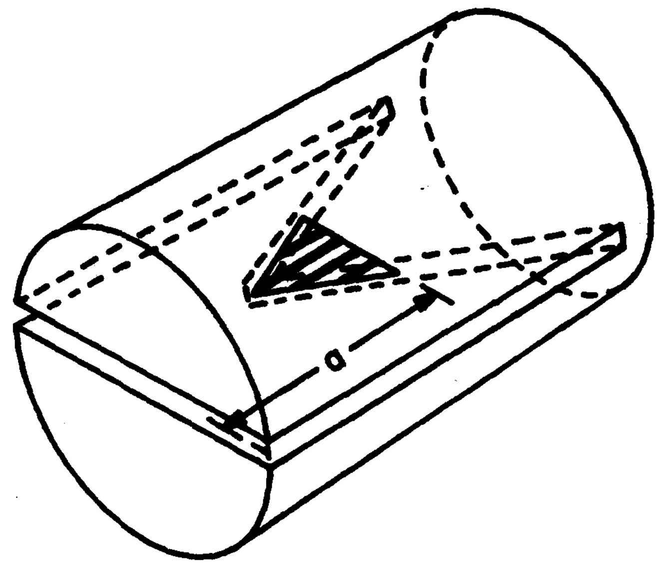

Figure 1. Short rod specimen with crack denoted by the shaded area.

EXPERIMENTAL

The material used for these tests was Kawecki Berylco CIP/HIP-1 beryllium. Its density was 1.852 g/cm^3; its grain size was from 8 to 9 microns. Its elemental analysis was as follows (in parts per million):

BeO	Fe	Al	Mg	Si	C	Cr	Co	Cu	Pb	Mn	Mo	Ni
1.09×10^4	200	40	35	83	203	24	<5	40	1	13	<10	125

Five compact toughness (CT) specimens were machined from the beryllium and tested according to ASTM E 399-74, with the exception that the K_F used in fatigue was approximately 0.8 K_Q, and reversed loading (R = -2 to -3) was also used. These deviations from E 399-74 coincide with recommendations made by ASTM Task Group E24.01.11 on Fracture Testing of Beryllium.[4] The CT specimens were 15.9 mm thick, and had a W/B ratio[3] of 2. Figure 2 shows the tested specimen halves. The fatigue pre-cracked areas show as darker regions in the figure.

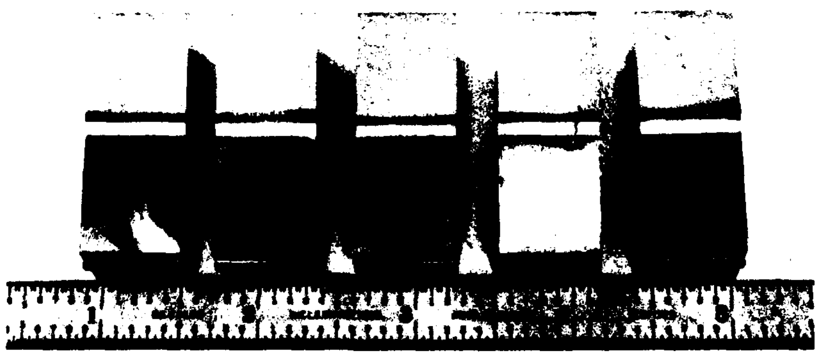

Figure 2. Photograph of the fractured surface of the beryllium compact toughness specimens.

After the five CT specimens were tested, a short rod fracture toughness specimen was machined from each of the ten CT specimen halves. The short rods and their slots were oriented such that the crack plane in the short rod would be parallel to the crack plane in the parent CT specimen. The short rod specimen dimensions are given in Figure 3. The slots which form the "V" in the specimen were 0.38 mm thick, and had curved bases because they were sawed by letting the specimen down onto a circular saw blade. For ease of measurement, the angle of the "V" was defined as the chord angle, as illustrated in Figure 3.

The short rods were tested using the Terra Tek Fractometer I,[6] a machine especially designed for testing short rod and short bar specimens of hard, brittle materials. Briefly, a fracture toughness test normally consists of inserting a very thin inflatable stainless steel bladder, called a "flatjack", into the slot in the front face of the specimen. The flatjack extends 6.12 mm into the slot, almost to the point of the V. The flatjack is then inflated with a high-modulus fluid (mercury), and contacts the inner walls of the slot. Further inflation then increases the pressure in the flatjack, thus imparting a distributed opening load in the specimen mouth.

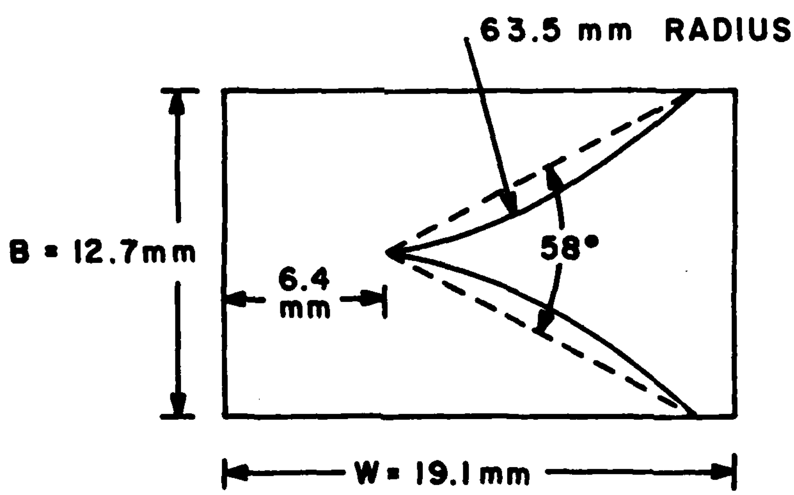

Figure 3. Dimensions of the beryllium short rod specimens.

The opening load causes a stress concentration at the point of the V in the specimen, such that a fracture first initiates there. Normally, the crack is initially quite stable because of the constant widening of the crack front as it propagates. Thus, an ever-increasing load is required initially to keep the crack moving. When the crack reaches a certain critical length, a_c, (about where it is shown in Figure 1), the crack-advancing load normally goes through a smooth maximum, and thereafter it decreases with further crack growth. It is found both experimentally and theoretically[5,6] that the crack length, a_c, at peak load is a constant for a given specimen configuration, independent of the specimen material, provided the specimen obeys the principles of linear elastic fracture mechanics (LEFM). Thus, the peak load in a short rod test is the load required to advance the crack when the crack length is a_c, and therefore, the peak load can be shown to be directly proportional to the critical stress intensity factor. In the case of flatjack loading of the short rod specimen, the fracture toughness is given by[6]

$$K_{Ic} = A_F P_c \sqrt{B} \ , \tag{1}$$

where P_c is the peak pressure in the flatjack during the test, B is the specimen diameter, and A_F is a dimensionless constant so long as the scaled specimen geometry remains constant. The value of A_F used for the short rod specimen geometry of this study (Figure 3) was

$$A_F = 8.26 \tag{2}$$

Although many short rod tests of fracture toughness are done as described above without making any plot of load vs. specimen mouth opening displacement, such plots can often be of value for detecting rate effects, stress corrosion cracking, abnormalities in apparent toughness along the crack path, etc. They can also be used to determine whether the specimen obeys the assumptions of linear elastic fracture mechanics, provided at least one relaxation of the load is done when the crack is in the vicinity of the critical crack length. Figure 4 shows a typical load-displacement record for a fracture toughness test of tungsten carbide/colbalt.

Load-displacement test records were made of each of the ten beryllium short rod specimens in order to extract the maximum information from the tests. Instead of smooth records like that of Figure 4, however, the beryllium load-displacement records all had the general appearance shown in Figure 5,

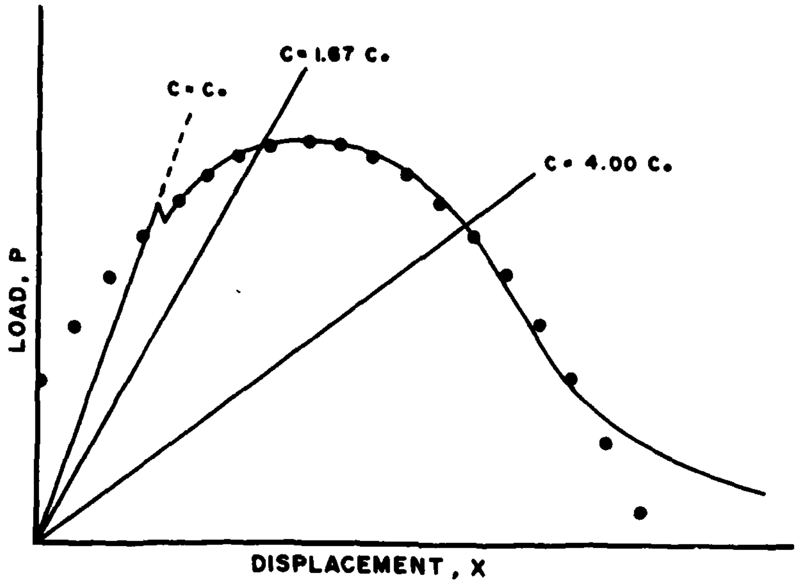

Figure 4. Typical load-displacement record for an LEFM short rod fracture toughness specimen. The solid line is the actual test record; the broken line is the standard curve model.

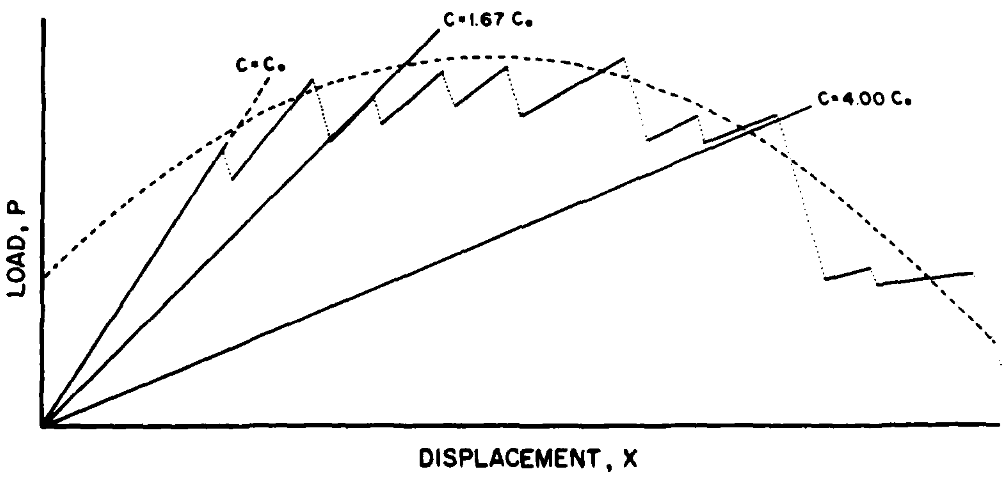

Figure 5. Load-displacement record for beryllium sample #3-2. The broken line is the standard curve model least squares fit to the top portion of the test record.

which is the plot of one of the tests. Although the loading was done smoothly and continuously, the crack would remain almost stationary until it would suddenly jump ahead, producing the audible "tick", a sudden decrease in load, and an increase in the specimen mouth opening. The crack would then remain almost stationary again until the next jump ahead, thus producing records like that of Figure 5. Although the Fractometer load-displacement plots at first appeared discouraging, they actually provided much more than the usual single critical stress intensity factor which allows a fast-moving crack to arrest. The data interpretation and data reduction procedures used for the beryllium data are discussed in the next section.

SHORT ROD DATA REDUCTION

In a normal LEFM short rod test, it is clear that the stress intensity factor at the crack tip is constantly at its critical value during the period of slow, steady-state crack growth. Thus, in a test record such as that of Figure 4, all points significantly beyond the initial linear elastic loading portion of the load-displacement path correspond to K_{Ic} conditions at the crack front. Any one of those points could be translated into a K_{Ic} measurement if the corresponding crack length and compliance derivative were known. It is convenient, of course, to use the peak load point on the load-displacement path to calculate K_{Ic}, because the dimensionless crack length, a_c/B, and the compliance derivative, $d[(cEB)/d(a/B)]_{ac\ /B}$ are always the same at that point, regardless of the specimen material. These quantities are contained in the short rod calibration constant, A_F (cf. Eq. 1 and 2).[6]

In the tests of beryllium, however, very few of the points on the load-displacement path correspond to K_{Ic} conditions at the crack tip, because significant crack growth initiated only at those points where crack jumps began. It was reasoned that if beryllium had not displayed the crack jump behavior (which is caused by the dynamic toughness, K_{Id}, being smaller than K_{Ic}), the load-displacement record would have been smooth, and would have passed through the points on the observed record where crack jumps initiated. Thus, if one could use the crack jump initiation points to reconstruct a smooth load-displacement record, the peak load on that record could be used in Equation 1 to calculate K_{Ic}.

A theoretical investigation showed that for a given scaled short rod specimen geometry, all normal LEFM load-displacement records such as that of Figure 4 can in principle be scaled to a single, standard load-displacement curve. Further, if the standard curve were known, any single K_{Ic} point on an actual load-displacement plot could be used to reconstruct the rest of the curve, complete with the P_c point from which K_{Ic} can be calculated.

Therefore, for reducing the beryllium data, a mathematical model of the standard LEFM load-displacement curve was derived. The relation, which adequately describes a substantial portion of the normal LEFM test record, is the quadratic

$$(1-s)P_c^2 - (P + \frac{2rs}{c_o} x) P_c + \frac{r^2 s}{c_o^2} x^2 = 0, \tag{3}$$

where P_c is the peak load on the curve, P and x are the load and displacement at any point on the curve, c_0 is the initial elastic loading compliance of the specimen as measured from the load-displacement test record, and r and s are dimensionless constants whose values for the specimens of this study, as determined by fitting Equation 3 to several normal LEFM experimental curves, are approximately

$$\begin{aligned} r &= 0.50 \\ s &= -0.60 \end{aligned} \tag{4}$$

Equation 3 is written in the form of a quadratic in P_c, and assumes that the origin of the P,x coordinates is at the start of the initial linear elastic loading path. The coefficients of P_c for any given crack jump initiation point are determined from the values of r and s (Equation 4), from the (P,x) coordinates of the crack jump initiation point, and from the initial elastic compliance,

$$c_o = \frac{\Delta x}{\Delta P}, \tag{5}$$

evaluated along the slope of the initial loading path on the test record. Hence, the evaluation of the fracture toughness of a beryllium specimen from its short rod load-displacement curve was practicable. First, for a particular test record, such as that of Figure 5, the value of P_c in Equation 3 was found for one crack jump initiation point (P,x). The value of P_c was used in Equation 1 to find the value of K_{Ic} for that point. This procedure was repeated for several crack initiation points on each load-displacement record. The average of the K_{Ic} values obtained in this way from each specimen is reported in Table 1.

Since nonplane strain effects on the crack are more pronounced in the initial region and in the final region of crack growth, the load-displacement points used to evaluate the fracture toughness should correspond to crack lengths of intermediate size. Because the compliance of a specimen is related to its crack length, the compliance at a P,x data point in question, taken as c = x/P, was used to judge the acceptability of the point in calculating the

toughness. Data points in the compliance range $1.67c_0 < x/P < 4.00\ c_0$ were taken as acceptable for this study. The values of r and s (Equation 4) were selected to produce a good match of several experimental normal LEFM curves over this compliance range. Figure 4 shows the compliance range and the fit of Equation 3 to one of the normal LEFM records used to evaluate r and s.

Just as the load-displacement points at which crack jumps initiated correspond to K_{Ic} data points, the load-displacement points at which crack arrest occurred correspond to the stress intensity factor which allows a fast-moving crack to arrest, K_{Ia}. By using crack arrest points in the above procedure, several values of K_{Ia} were also obtained from each test record.

RESULTS AND DISCUSSION

Table 1 presents a summary of the beryllium fracture toughness data obtained from the CT and the short rod specimens, including the K_{Ia} values obtained from the short rod tests. Although the CT tests did not meet the ASTM fatigue pre-cracking requirement, the toughness values are listed as K_{Ic} values, inasmuch as an ASTM task group has recommended relaxing the fatigue pre-cracking requirement for beryllium.[4]

The average of the five CT toughness values for the beryllium of this study is 10.40 $MPa\sqrt{m}$, with a standard deviation of 4.5 percent. The average toughness for the ten short rod beryllium specimens was only 2.3 percent higher, 10.63 $MPa\sqrt{m}$, with a standard deviation of 3.0 percent. These results agree with the values of fracture toughness reported by Conrad, et. al.,[4] for a similar beryllium pressing as measured by several laboratories for a round robin test program conducted for NASA-Lewis. The average of their values was 10.37 $MPa\sqrt{m}$, with a standard deviation of 7 percent. Apparently, part of the scatter in the reported data is due to lab-to-lab variations, since the average standard deviation reported by each individual laboratory participating in the study was only 5.5 percent.

It is interesting to compare the standard deviation of the CT tests to the standard deviation of the short rod tests performed for this study. The improved standard deviation in the short rod tests is undoubtedly due to the averaging of several K_{Ic} values in obtaining the K_{Ic} for each short rod specimen. If the standard deviation is calculated for the individual values obtained from each crack jump initiation point, the result is 5.0 percent on a total of 40 K_{Ic} data points. The average standard deviation of the individual K_{Ic} values obtained from a given short rod specimen was 4.3 percent for an average of four data points per specimen.

Since the standard deviations of individual K_{Ic} measurements of Ref. 4 and of this study tend to be around 5 percent, it may be that this amount of scatter is a characteristic of the material. This fact, as well as the average value of K_{Ic}, should be taken into account in any design considerations.

The average stress intensity factor for crack arrest in the beryllium short rod specimens was 9.41 $MPa\sqrt{m}$ with a standard deviation of 2.8 percent.

TABLE 1—*Summary of beryllium fracture toughness data.*

CT Spec. No.	K_{Ic} (MPa$\sqrt{m}$) (per E 399)[a]	Short Rod Spec. No.	K_{Ic} (MPa$\sqrt{m}$) (Short Rod)	For Crack Arrest: K_{Ia} (MPa$\sqrt{m}$) (Short Rod)
1	10.30	1-1	10.89	9.71
		1-2	10.25	9.07
2	11.20	2-1	10.94	9.46
		2-2	10.76	9.54
3	10.22	3-1	10.33	9.15
		3-2	10.64	9.63
4	9.96	4-1	10.76	9.53
		4-2	10.80	9.38
5	10.30	5-1	10.02	8.94
		5-2	10.90	9.66
Average	10.40		10.63	9.41
Stan.Dev. (%)	4.5		3.0	2.8

[a]Except for fatigue pre-cracking.

This value is almost 90 percent of K_{Ic} for the material. This crack arrest toughness is not inconsistent with values reported in the literature,[1] which vary from 63 percent to 93 percent of crack initiation toughness. However, it was noted that the short rod values of K_{Ia} tended to be smaller when the crack length at arrest was small, and progressively increased with increasing crack length. To illustrate, the ten-specimen average K_{Ia} obtained from the first crack arrest point which fell within the accepted compliance range was 8.98 MPa$\sqrt{m}$, while the ten-specimen average from the last arrest point to fall within the range was 9.84 MPa$\sqrt{m}$. This effect may be related to the dynamics involved in crack arrest, and to the fact that the crack surface area generated per unit length of crack advance is small initially in the chevron-notched short rod specimen, but increases with the crack length. Thus, the distance the crack can "coast" while using up the kinetic energy stored in the specimen arms should be greater for small crack lengths than for larger ones. Because of the relatively stiff machine loading conditions, the additional "coasting" of the crack at small crack lengths would tend to yield a smaller load at the final arrest point, and therefore a decreased calculated value of K_{Ia}. No such dynamic effect influences the values measured for K_{Ic}, of course.

The present test series serves as a check on the short rod calibration constant for flatjack loading, A_F. The value of A_F was originally based on the value of A, which is the short rod calibration constant for grip loading conditions. However, a preliminary experimental compliance calibration,[8] plus other evidence, led to increasing the value of A_F by ten percent to its present value of 8.26. The agreement between the CT and short rod specimen results of this study indicates that the upward adjustment in A_F was approximately correct.

Material and time economies should be possible by using the short rod method. Because of the several toughness values yielded by each short rod test, fewer tests may be needed to obtain a good estimate of beryllium fracture toughness; a four-fold decrease in the number of tests may be possible. Also, the short rod specimen is much smaller than the CT specimen. Little time is required for each test: about two minutes to run the actual test, and about 20 minutes to do the data reduction using a programmable hand calculator. It is even possible to obtain fairly accurate toughness values by visually matching a smooth curve to the test data.

SUMMARY

Two fracture toughness test series were run on one batch of CIP/HIP-1 beryllium. The material was first machined into CT test specimens, tested, and then the tested halves were machined into short rods and tested. The agreement was very good between the results of the two test series. The toughness as indicated by the CT tests is 10.40 MPa$\sqrt{m}$ with an associated standard deviation of 4.5 percent. The toughness according to the short rod tests is 10.63 MPa$\sqrt{m}$ with a standard deviation of 3.0 percent. The values obtained in this study for the fracture toughness of beryllium compare favorably with previously published results for a similar beryllium pressing, where the average fracture toughness for the five best data sets was 10.37 MPa$\sqrt{m}$, and the average standard deviation was 5.5 percent. The better-than-average grouping of the short rod test results is due to the fact that each specimen toughness value represents the average of several individual toughness readings. Hence, there may be required fewer short rod tests than CT tests to obtain an adequate estimate of the fracture toughness of a particular beryllium pressing. Also, a measure of the crack arrest toughness is easily obtained from short rod tests. These facts, coupled with the ease of making and testing short rods, should make the short rod method a desirable way to test the fracture toughness of beryllium.

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Army Materials and Mechanics Research Center,
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Lynn M. Barker - Terra Tek, Inc.
Randall V. Guest - Terra Tek, Inc.

Final Report AMMRC TR 79-31, May 1979, 25 pp. -
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